Development Lines of Improved Physical Modeling for Aerodynamic Design

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$C^2A^2S^2E$ Center for Computer Applications in AeroSpace Science and Engineering

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Outline

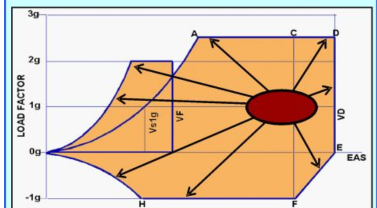
- Introduction
- Reynolds stress models (RSM)
- Scale resolving simulations (SRS)
- Transition prediction and modeling
- Conlusion

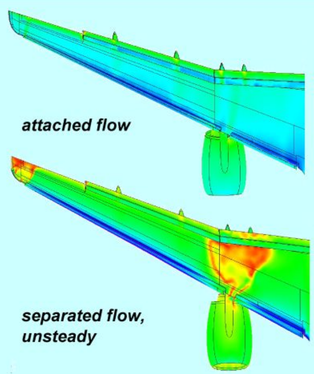
Vision: The Digital Aircraft

Future goal for CFD

- Aircraft design and analysis based strongly on numerical simulation
- Bring down number of computations necessary and free from **current** configuration knowledge
- Two basic concepts
  - Time accurate maneuver simulations: ***Flying the equations***
  - Generation of aerodynamic/aeroelastic data: ***Flying through the data base***
- DLR project Digital-X, currently underway

Full flight envelope coverage: *CFD mostly done near cruise point*





configurations:

clean

airbrakes deployed

high lift

50	flight points
100	mass cases
10	a/c configurations
5	maneuvers
20	gusts (gradient lengths)
4	control laws

~ 20,000,000 simulations

Engineering experience for **current** configurations and technologies

~ 100,000 simulations

Vision: The Digital Aircraft

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- Aircraft design and analysis based strongly on numerical simulation
- Bring down number of computations necessary and free from **current** configuration knowledge
- Two basic concepts
  - Time accurate maneuver simulations: ***Flying the equations***
    → **Physical Modeling for High Fidelity CFD**
  - Generation of aerodynamic/aeroelastic data: ***Flying through the data base***
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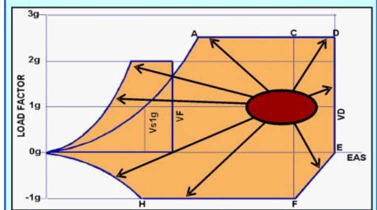

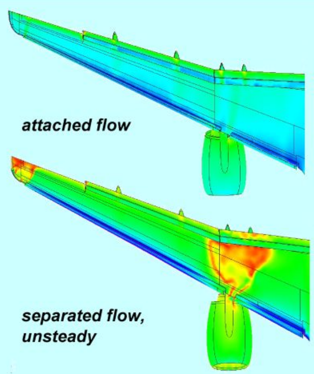

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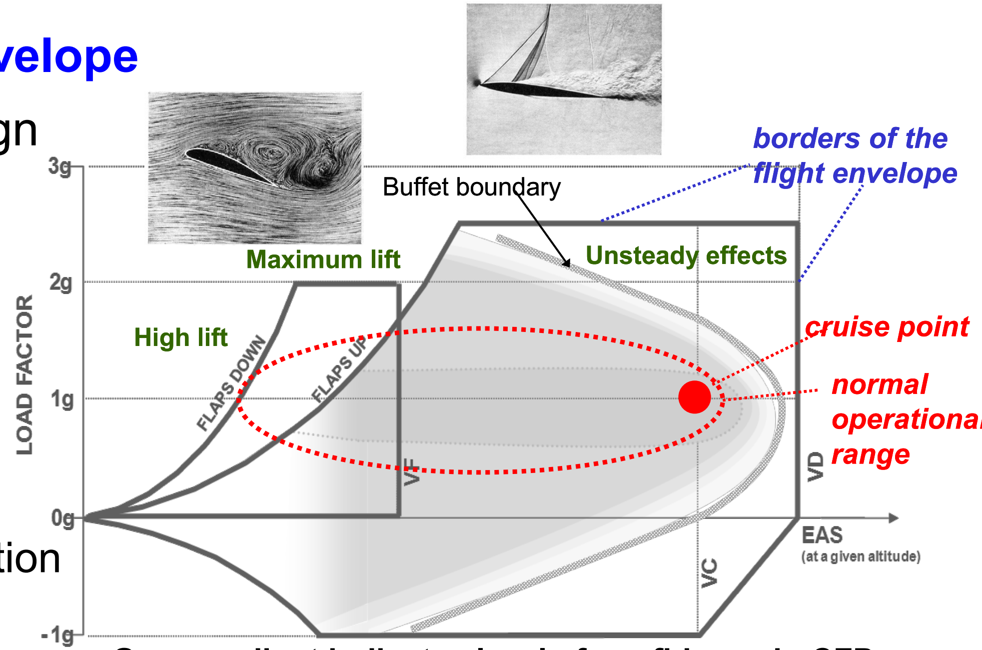
Vision: The Digital Aircraft

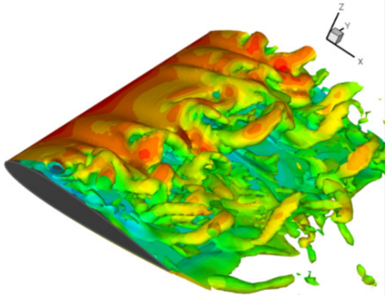
Numerical Analysis of Full Flight Envelope

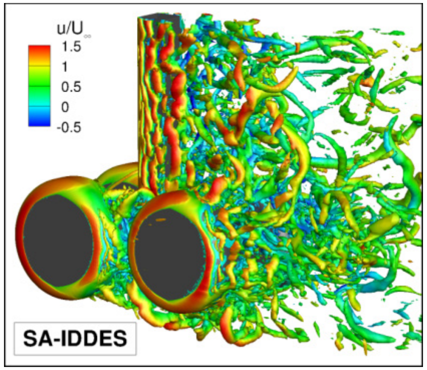
- Today, very reliable results for design point applications.
- Tomorrow, same reliability needed for complete flight envelope.
  - Strong non-linearities
    - Separated flow regions
    - Strong shocks
    - Shock/boundary-layer interaction
  - Unsteady flows
- In general, all major physical phenomema must be captured with sufficient accuracy.
  - Flow separation, boundary-layer representation, shock/BL interaction, …
  - Vortices, wakes, free shear layers, …
  - Engine jet flows, …
  - …



Grey gradient indicates level of confidence in CFD flow solutions

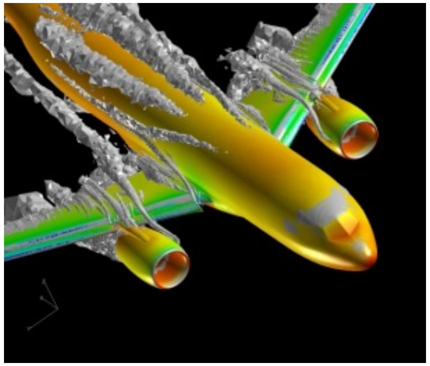
Vision: The Digital Aircraft

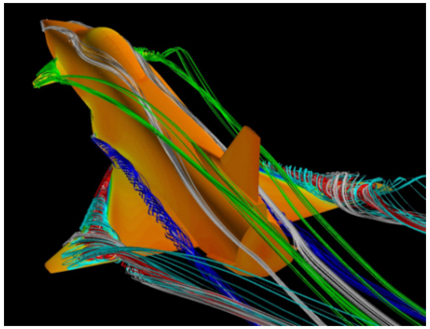




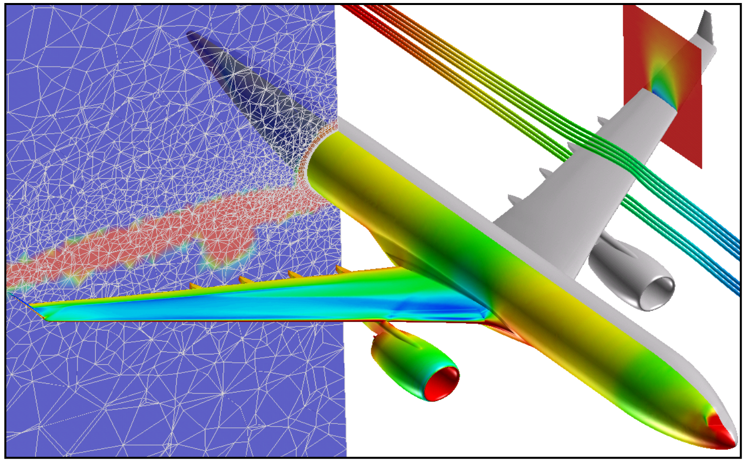
Numerical Analysis of Full Flight Envelope

- For accurate predictions, besides high grid resolution and accurate numerical handling of the equations **physical modeling** is a key issue.
- Three main development directions
  1. Reynolds stress models (RSM)
     - As standard RANS approach for highly complex industrial configurations
  2. Scale resolving simulations (SRS)
     - Improved numerical handling and modeling necessary for capturing incipient separation
     - RSM based hybrid RANS/LES & SAS approaches for components of aircraft or military configurations
     - Best practice for technical applications in industrial context
  3. Transition prediction and modeling
     - Necessary condition for accurate results of turbulence models within the full flight envelope



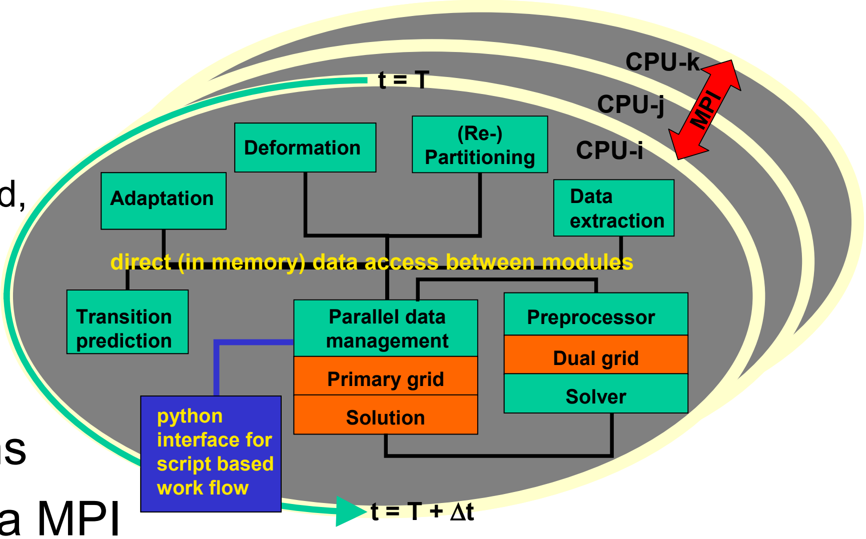


CFD tool



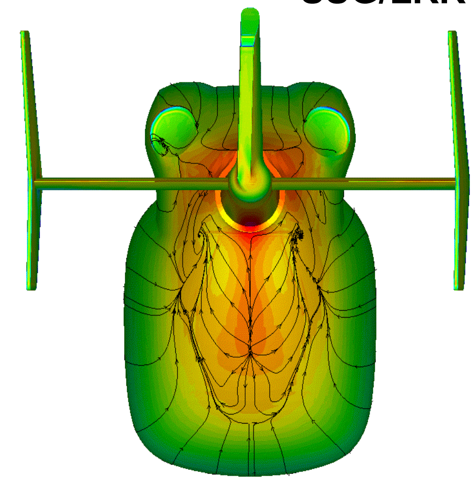
DLR TAU code

- Adaptive 2nd-order Finite Volume method for compressible RANS & hybrid RANS/LES on hybrid-unstructured meshes
  - Prototype for solver development
  - Prototype for multi-level parallelization
- Vertex-centered spatial scheme
  - edge-based dual-cell approach
- Steady (RK, LU-SGS; local time stepping, multi-grid, explicit residual smoothing, low-Ma preconditioning)
- Unsteady (dual-time stepping)
- Scalar or matrix artificial dissipation
- Interfaces for multi-disciplinary simulations
- Parallelization: Domain Decomposition via MPI
- Turbulence models (EVM, RSM, hybrid RANS/LES)
- Transition (e^N method within transition prediction module)



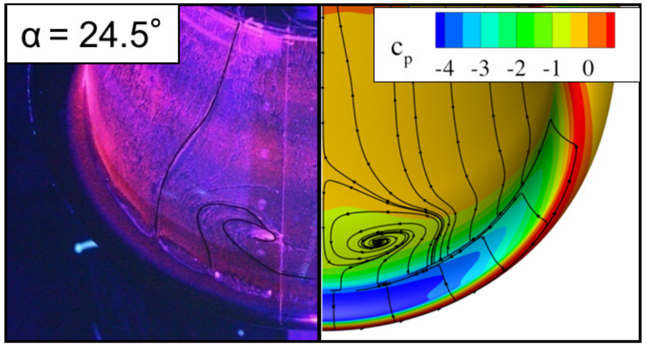
Reynolds stress models

SSG/LRR-ω



Differential RSM (DRSM)

- DRSM represent highest level of RANS-modeling
  - Individual equations for stress components
    → Anisotropy of turbulence accounted for
  - Effects of rotation and streamline curvature included
    → No corrections for free vortices necessary
  - No stagnation point anomaly
  - 7 model equations
- Sometimes lack of robustness for complex configurations
- DRSM in TAU
  - SSG/LRR-ω model
    - Based on Menter's BSL ω-equation
    - Standard model
  - ε^h-JHh-v2 model (Jakirlic-Hanjalic + ISM of TU-BS)
    - Based on homogeneous dissipation rate ε^h
    - Advanced near-wall treatment
    - Anisotropic dissipation



Oil-flow picture (left) and JHh-v2 RSM (right)

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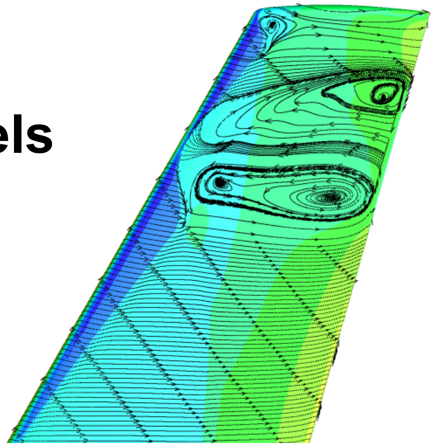
Reynolds stress models

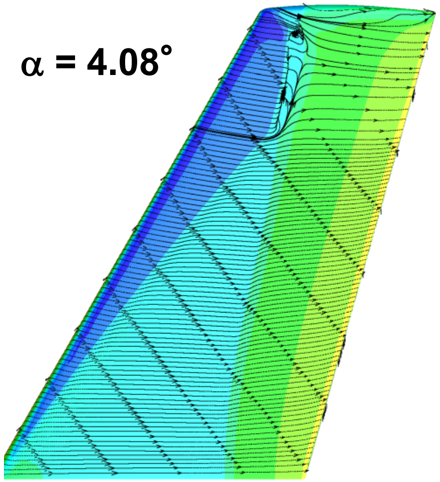
Application of Reynolds Stress Models

ONERA M6 wing

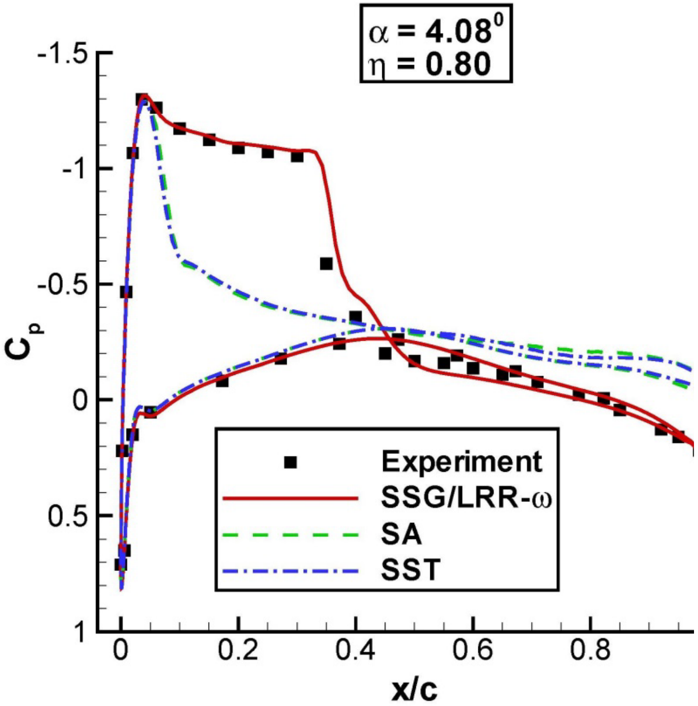
Re = 11.72×10^6, M = 0.84

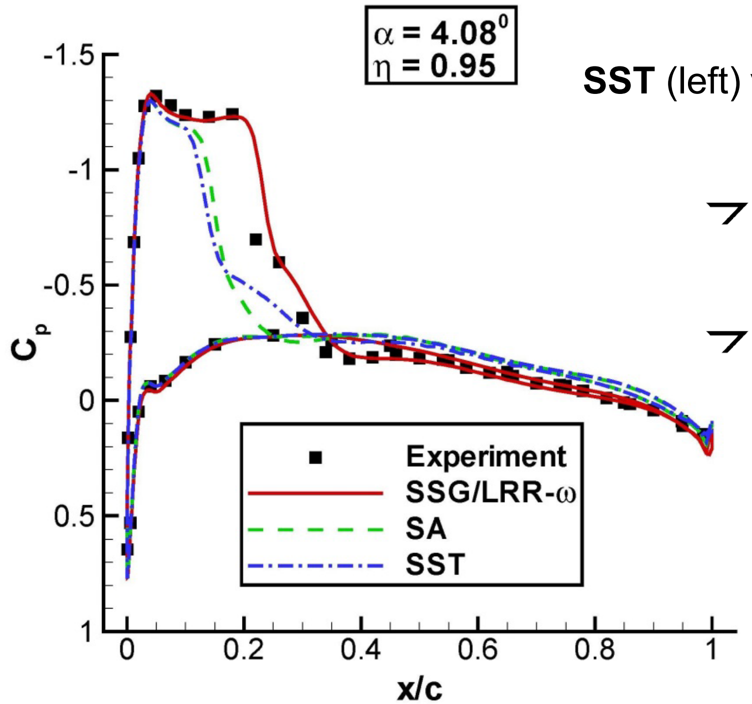


α = 4.08°



SST (left) **vs. SSG/LRR-ω** (right)





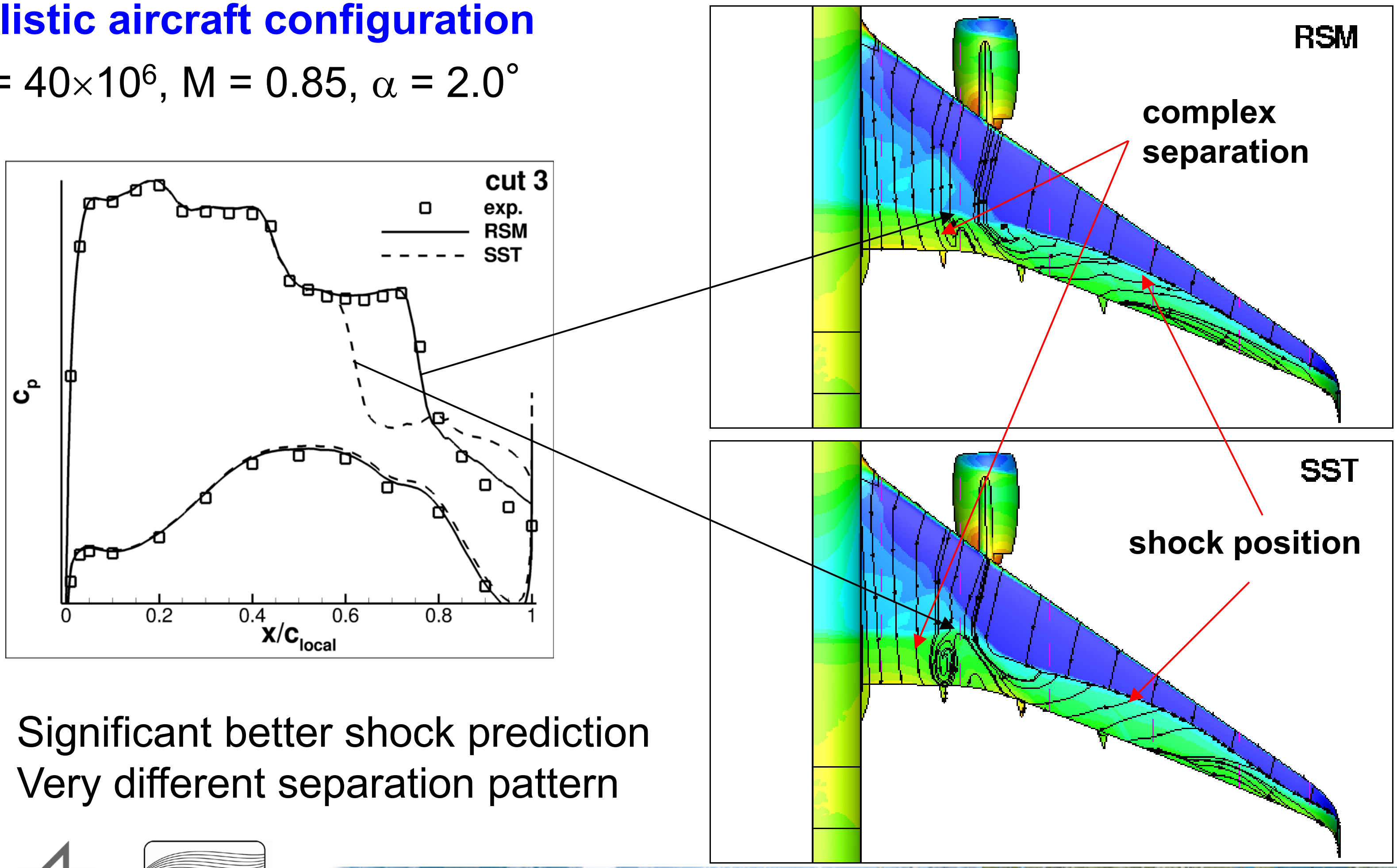
- Significant better shock prediction
- Very different separation pattern

Reynolds stress models

Application of Reynolds Stress Models

Realistic aircraft configuration

$Re = 40 \times 10^6$, $M = 0.85$, $\alpha = 2.0°$



- Significant better shock prediction
- Very different separation pattern

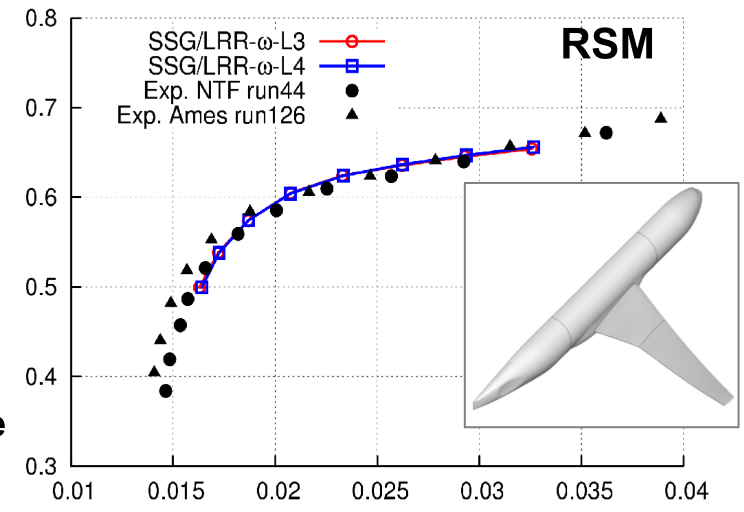
Reynolds stress models

Application of Reynolds Stress Models

NASA Common Research Model (CRM), DWP-4

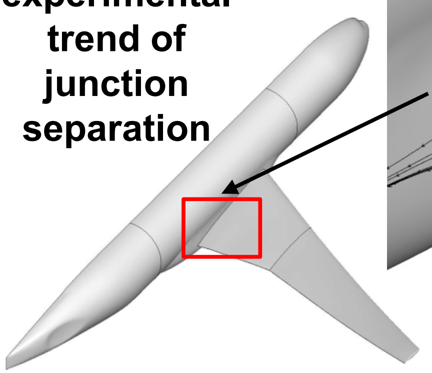
Re = 5×10^6, M = 0.85, α = 2.0, 2.75, …, 4.0

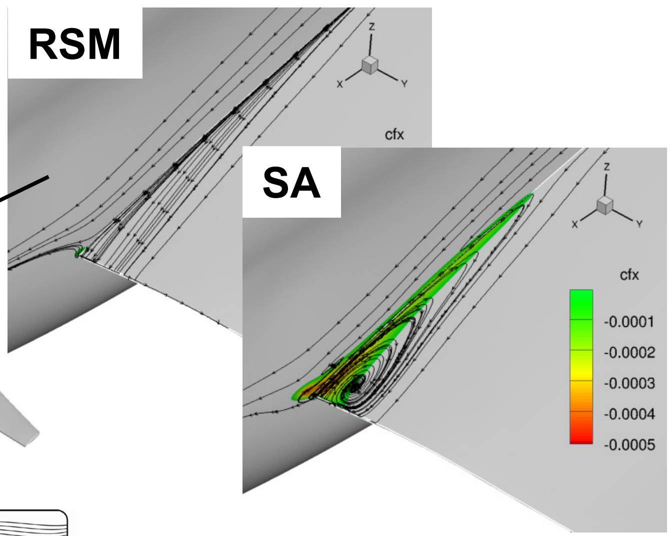
Grids: **L3(5M), L4(17M)**

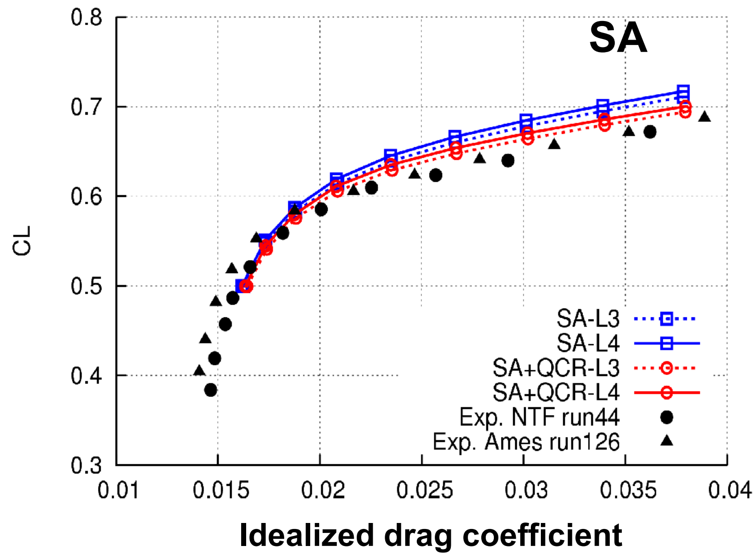


RSM shows very low grid dependence

RSM yields experimental trend of junction separation







Quelle: Diss. A. Probst

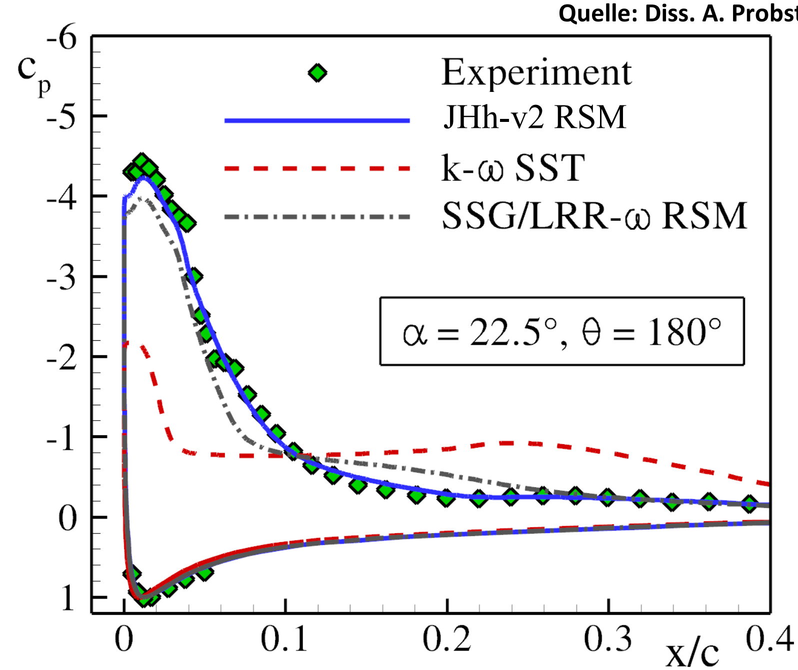
Reynolds stress models

Application of Reynolds Stress Models

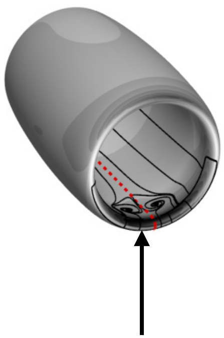
Flow-through nacelle at stall

Re = 1.3×10^6, M = 0.11

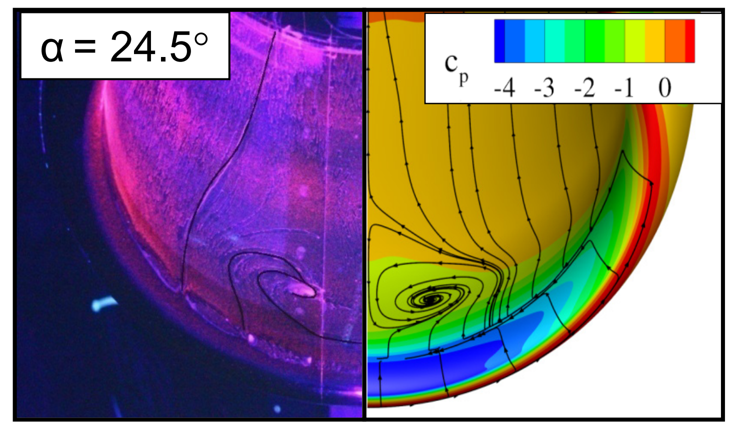
- URANS combined with e^N method
- Measured separation onset around α ≥ 24°
- Improvement by DRSM
- In particular ε^h-JHh-v2 model
  - Coefficients depend on turbulence quantities
  - Uses ε^h instead of ε: by targeted calibration mathing with DNS data near walls achieved



Surface pressure in inlet symmetry plane



θ = 180°



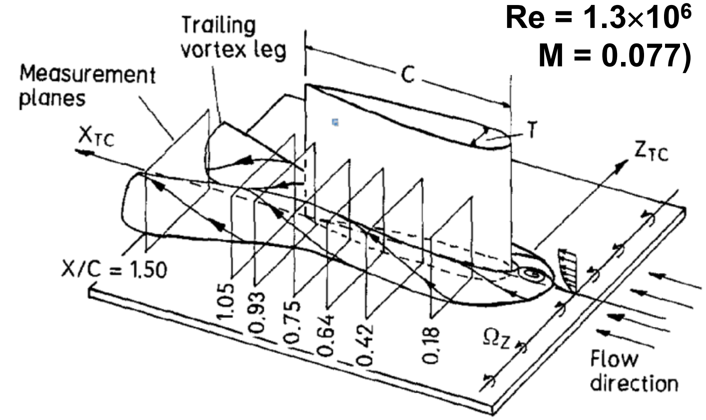
Oil-flow picture (left) and JHh-v2 RSM (right)

Reynolds stress models

Latest and future developments

- SSG/LRR-g model
  - Exact transformation of ω to $g=1/\sqrt{\omega}$
  - Higher numerical stability
  - No grid dependence of g near solid walls
  - No convergence with SSG/LRR-ω possible

Simpson wing
Re = 1.3×10^6
M = 0.077)



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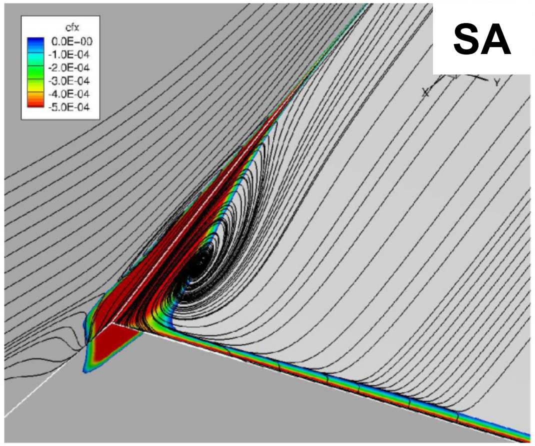
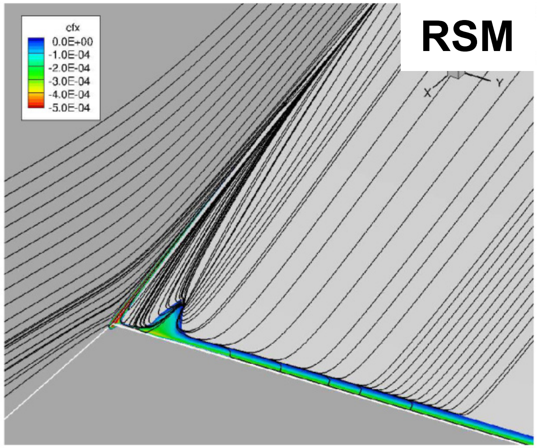
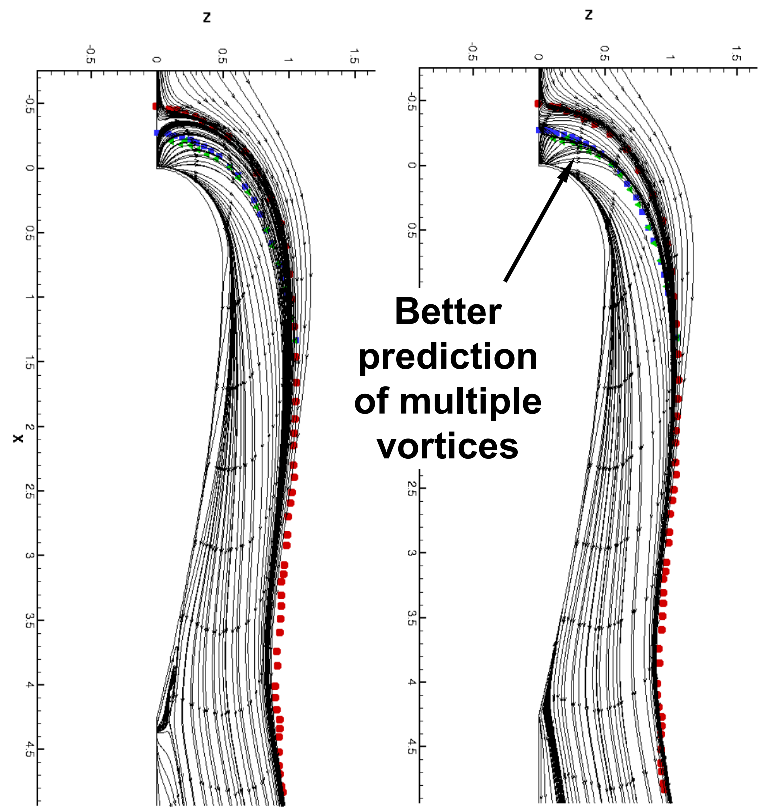
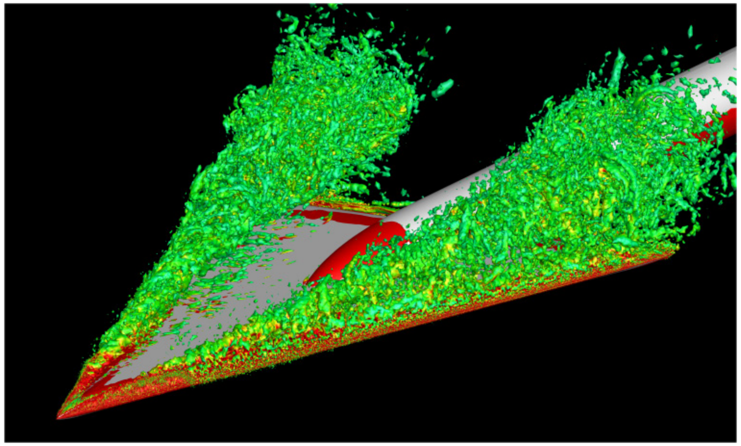






Scale resolving simulations



Delta wing model, iso-Q contours coloured with vorticity

Basic approach

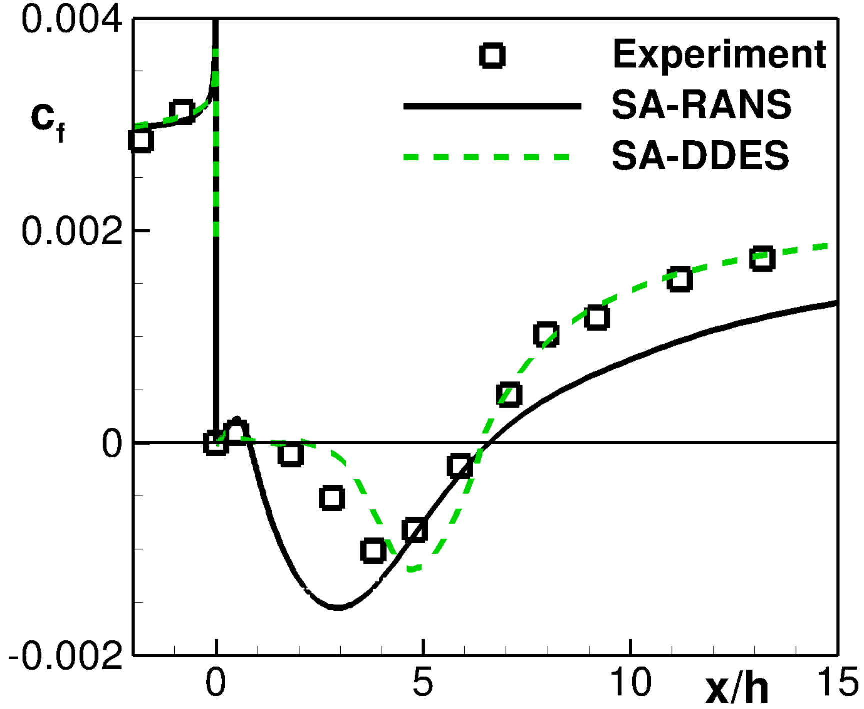
- Classical hybrid RANS/LES models
  - Detached-Eddy Simulation (DES, 1997)
  - Delayed DES (DDES, 2006),
  - Improved DDES (IDDES, 2008)
  - Coupled with SA or k-ω type RANS models
- Numerics
  - 2nd order central spatial discretization of all equations
  - 4th order matrix artificial dissipation with $k^{(4)} = 1/128$
  - Skew-symmetric convective fluxes (for kinetic energy conservation)
  - Low Mach number preconditioning (LMP) for M < 0.3
  - 2nd order dual-time stepping
- Range of applicability
  - Flows with massive local separations
  - Clear distinction between attached (stable) and separated (unstable) regions

Scale resolving simulations

Sample applications of basic approach

Generic flow case

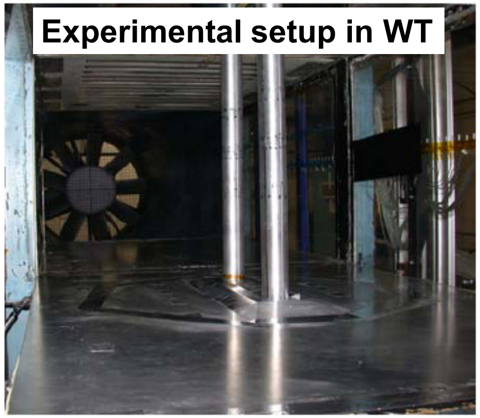
- Backward-facing step
  - Driver/Seegmiller case
  - Re_h = 38,000



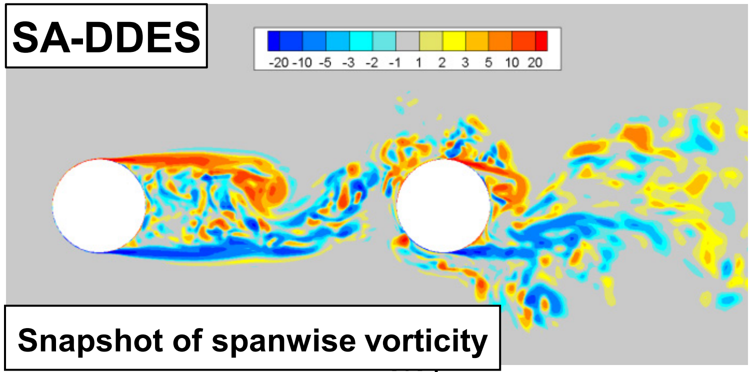
Scale resolving simulations

Sample applications of basic approach

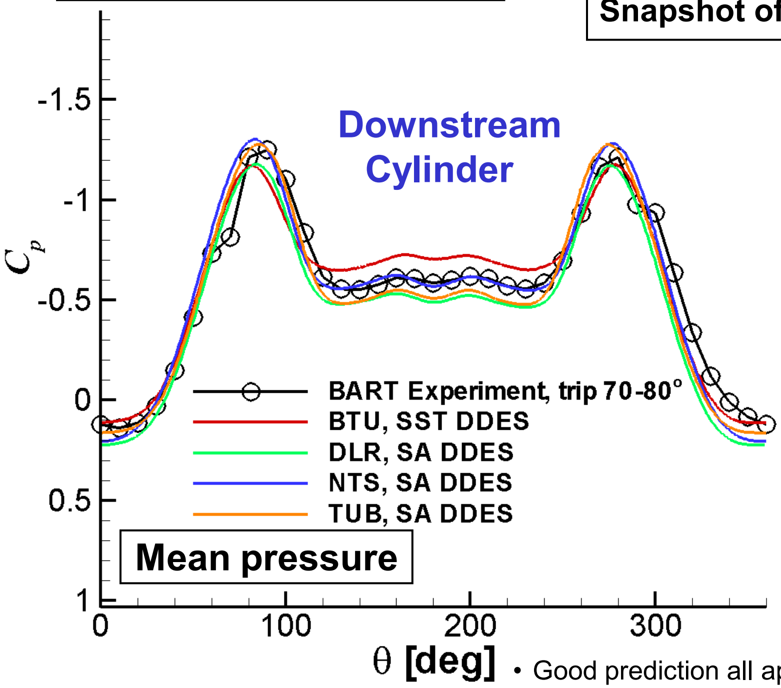
NASA tandem cylinder

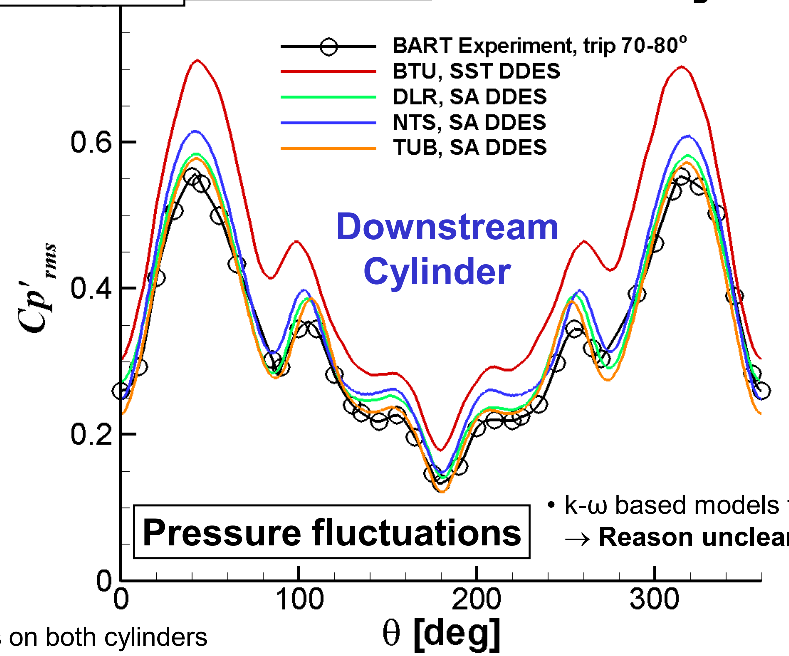


- **L/D = 3.7**
- **M = 0.1285**
- **Re_D = 1.66×10^5**



TAU results: **green**



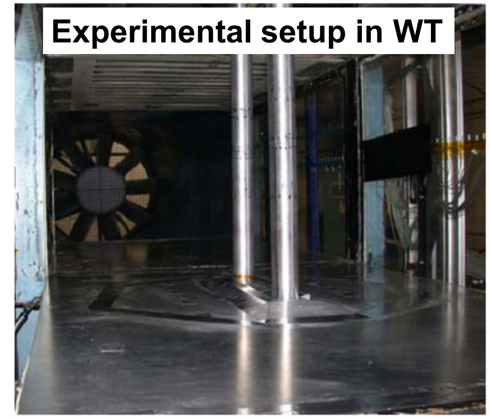


- k-ω based models too "noisy"
  → **Reason unclear**

- Good prediction all approaches on both cylinders
- Influence of numerical method and underlying RANS model small

Scale resolving simulations

Sample applications of basic approach



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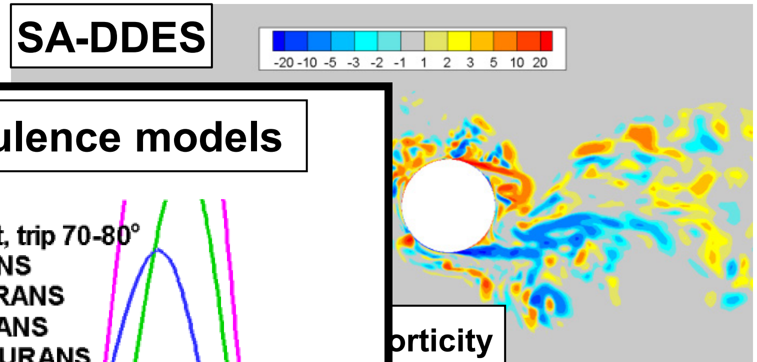
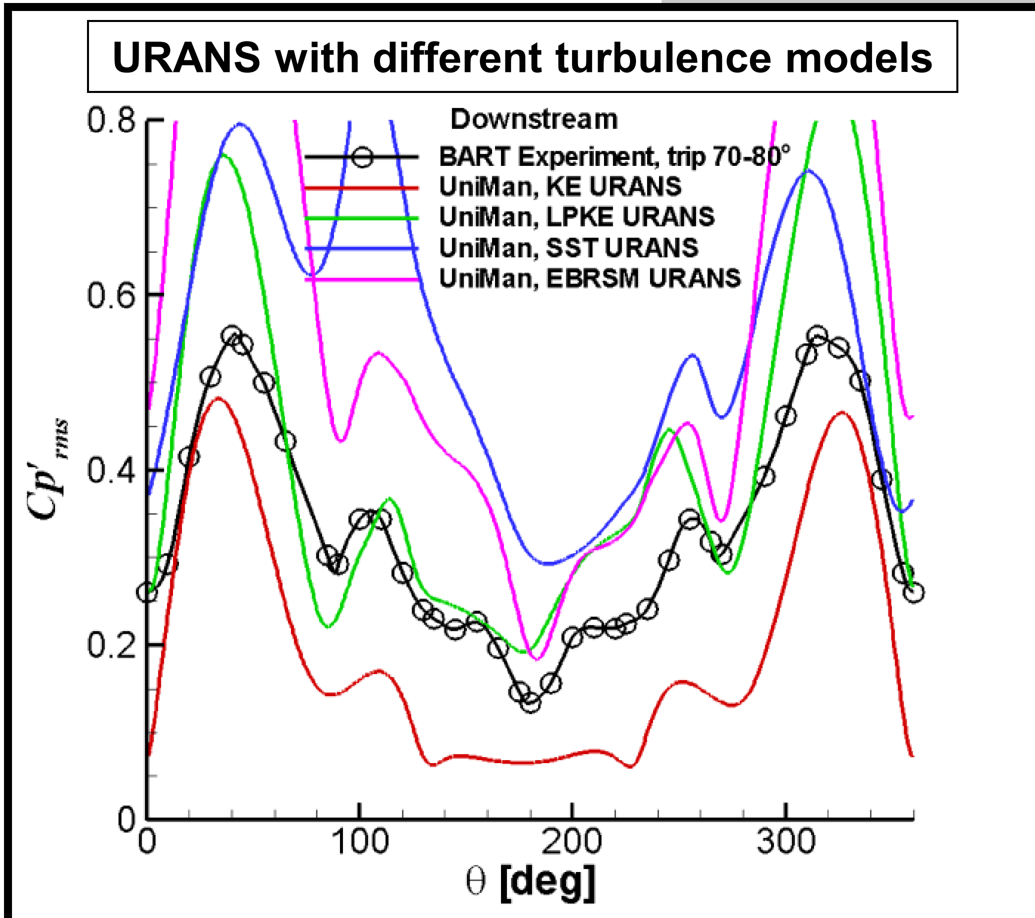
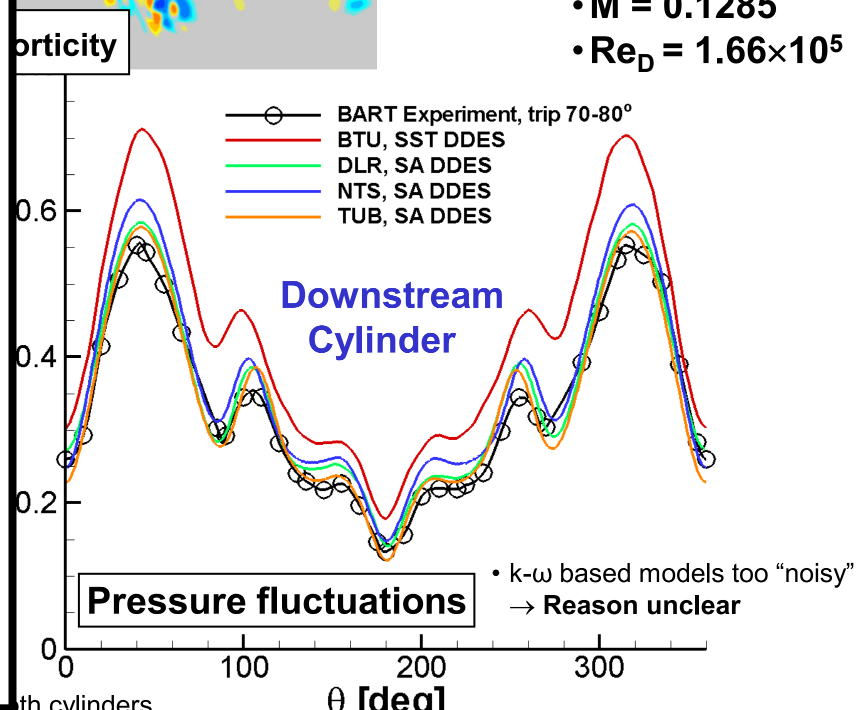






- k-ω based models too “noisy” → **Reason unclear**

…th cylinders

- Influence of numerical method and underlying RANS model small

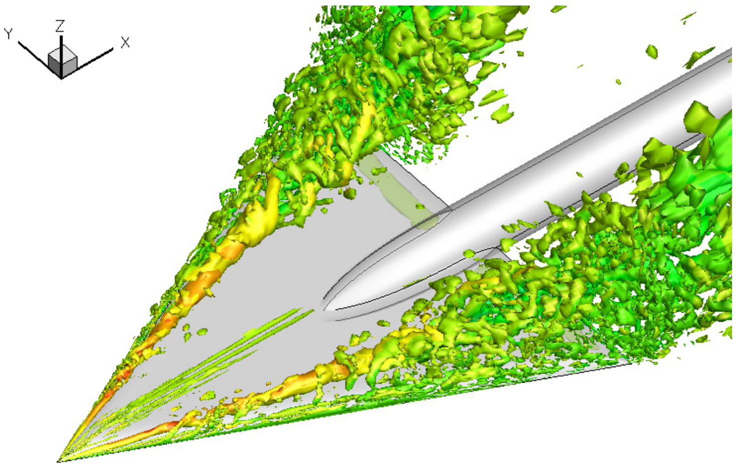
Scale resolving simulations

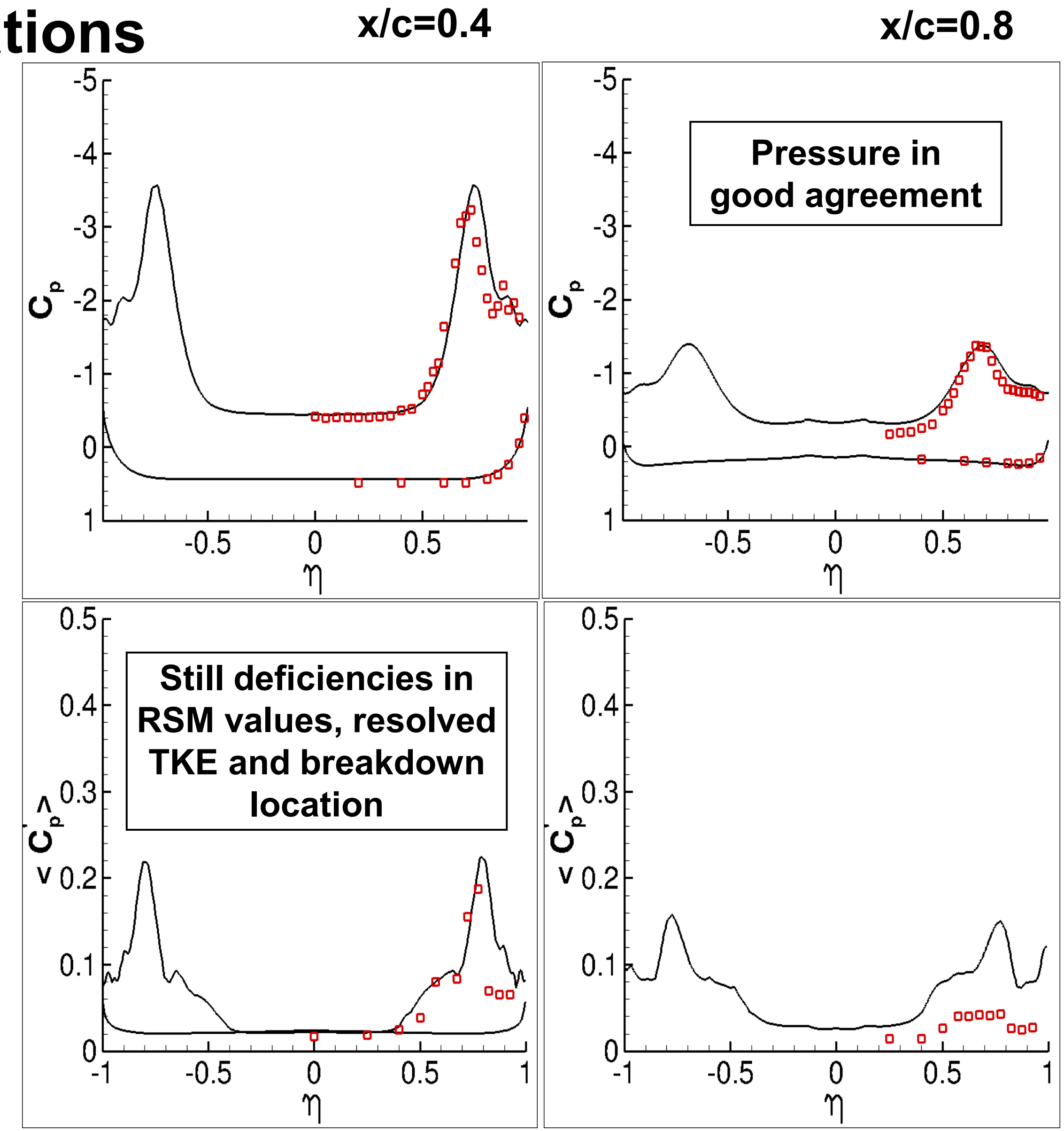
Sample applications

Delta wing with sharp LE

Re = 1.0×10^6, M = 0.07, α =23°

Vortex breakdown



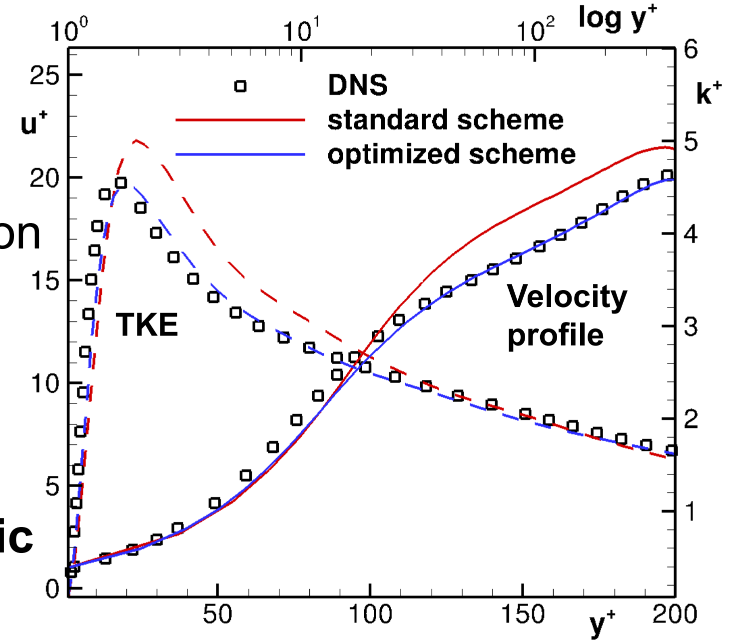


Scale resolving simulations

Extended approach

- **Improved Numerics**
  - Better satisfying general LES requirements
    → Very high accuracy → very low dissipation
    - Optimized scheme: 2^{nd}-order central scheme with **strongly** reduced diffusion characteristics
  - Establish optimized numerics for LES
  - Test with pure LES applications, e.g. **periodic 2D channel flow**
  - Switch of standard RANS scheme into optimized scheme for LES: apply optimized numerics in LES regions only
    → Adaptive numerical scheme for hybrid RANS/LES computations

WR-LES: given Re_δ (mass flow), target quantity Re_τ (wall shear stress)



	Re_τ
DNS	**395**
standard	358
optimized	393

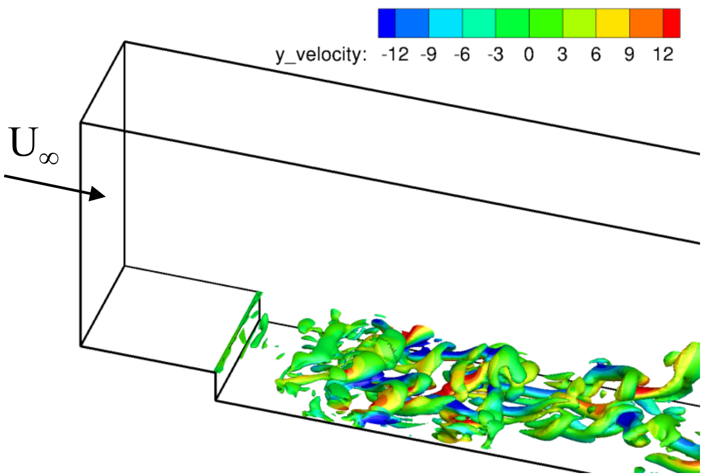
Scale resolving simulations

Sample applications of extended approach

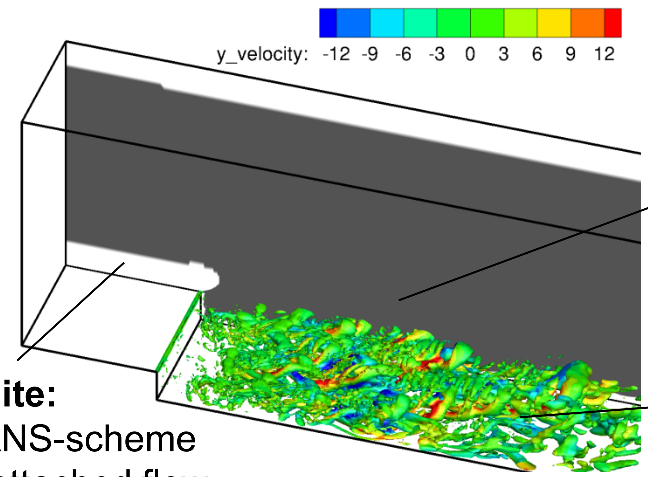
Flow separation at backward facing step (BFS)

- SA-DDES of backward-facing step; Re_h = 38,000
- Optimized scheme in LES region, standard stable scheme in RANS region
- Switch based on suitable sensor function (l_{hyb}/l_{RANS} sensor)

Standard scheme



Optimized scheme: adaptive RANS/LES numerics



grey:
Optimized LES-scheme in separated/re-attachment region

white:
RANS-scheme in attached flow

Improved resolution in LES region (Q-criterion)

Scale resolving simulations

Extended approach

- **Improved Modeling** → *Towards extending the applicability range from massive to incipient separation*
  - RANS/LES sensors for pressure-induced separation
  - Transition from RANS to LES („grey area“ mitigation)
  - Underlying RANS model

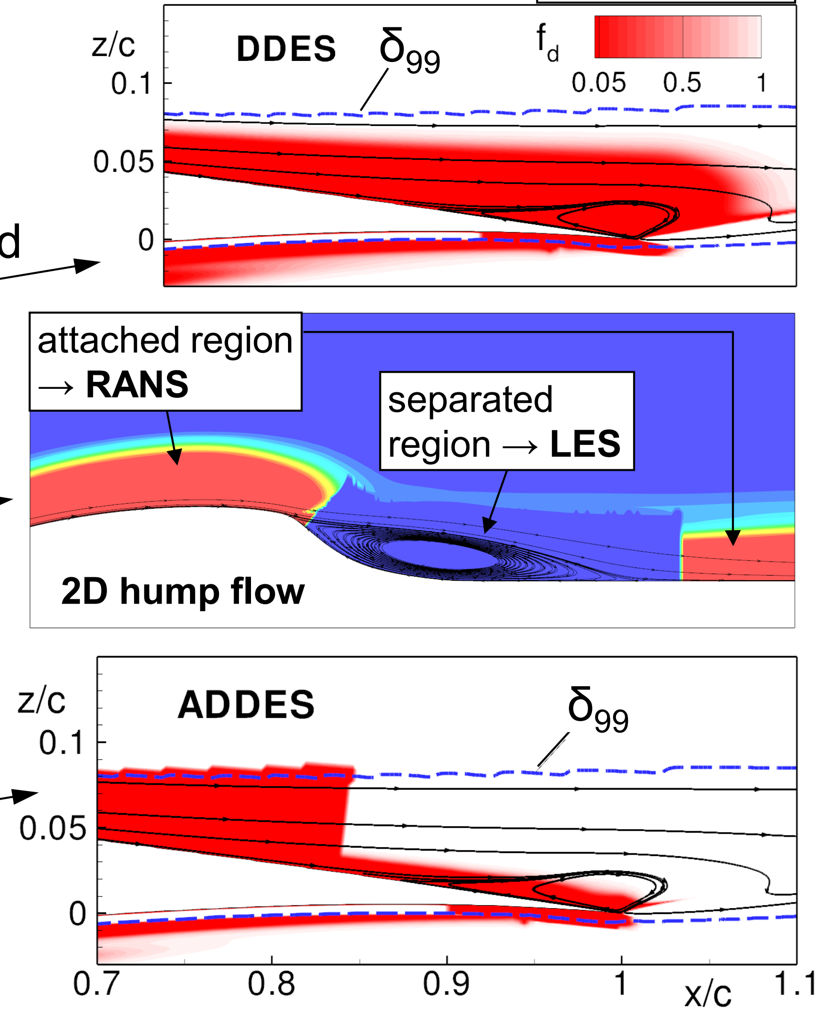
- RANS/LES sensors for pressure-induced separation
  - Identified shortcomings of DDES
    - No reliable “shielding” of attached BLs
    - No clear RANS/LES interface at separation
  - DLR development Algebraic DDES (**ADDES**)
    - Boundary-layer (BL) detection
    - Separation detection
    - Algebraic RANS/LES sensor

Scale resolving simulations

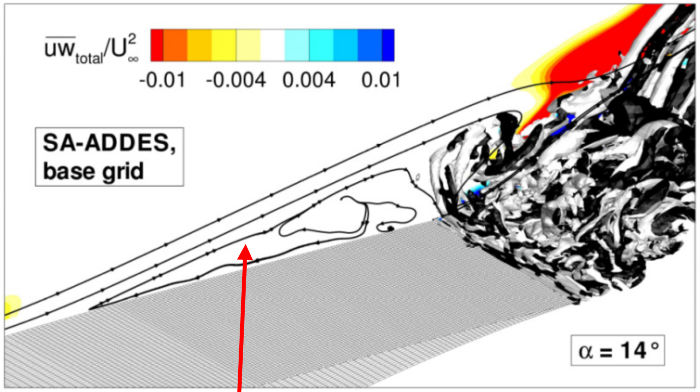
red: RANS
white: LES

Extended approach

- **Improved Modeling** → ADDES
  - RANS/LES sensors for pressure-induced separation
    - **BL detection**
      - algebraic BL criteria for U_{edge}
      - search algorithm to detect δ_{99}
    - **Separation detection**
      - Shape factor $H = \delta^* / \Theta \rightarrow H_{crit}$ as separation criterion (Castillo et al., 2004)
    - H_{crit} RANS-model dependent → calibration necessary
    - **Algebraic RANS/LES sensor**
    - RANS mode if: $d_w < \delta_{99}$ and $H < H_{crit}$
    - LES mode if: $H > H_{crit}$



Scale resolving simulations



Extended approach

- Transition from RANS to LES
  - Hybrid RANS/LES of incipient separation suffers from “grey area”:
    - Weak separations rather stable w.r.t. outer disturbances
    - Hybrid RANS/LES switches to LES mode, but resolved turbulence is delayed
  - Undefined modelling state with low total (modelled + resolved) turbulent stress

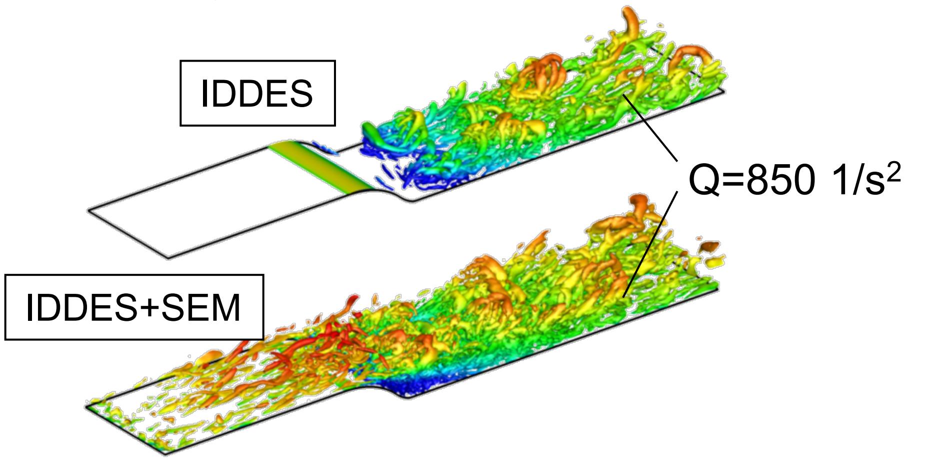
- Techniques for grey area mitigation considered in TAU code:
  1. **Stochastic forcing** of modeled turbulence
  2. Modified **LES scale** considering **local vorticity** vector
     - Both 1. and 2. applicable to rather unstable separation or free shear flow
  3. **Synthetic turbulence** generated from RANS data
     - Complex approach, but applicable to weakly separated or attached flow

Scale resolving simulations

Extended approach

- **Improved Modeling** → Synthetic turbulence (RANS → LES)
  - Transition from RANS to LES
  - Initial implementation of **Synthetic Eddy Method** (SEM, 2006)
    - Artificial fluctuations generated from given turbulence statistics
    - First tests with SEM applied at inflow boundary:
      - 2D channel flow
      - Rounded step with separation:

Method	$x_{separation}$	$x_{reattachment}$
IDDES	1.15	6.04
IDDES + SEM	0.72	4.99
LES (reference)	0.83	4.36



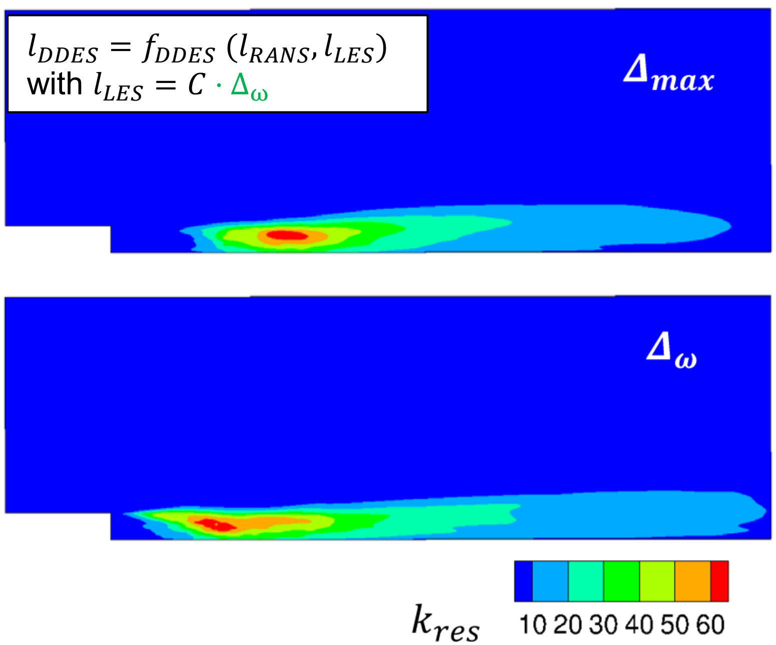
  - ***Open issues:***
    - unphysical non-zero divergence of synthetic turbulence
    - full integration in hybrid RANS/LES (i.e. combination with ADDES)

Scale resolving simulations

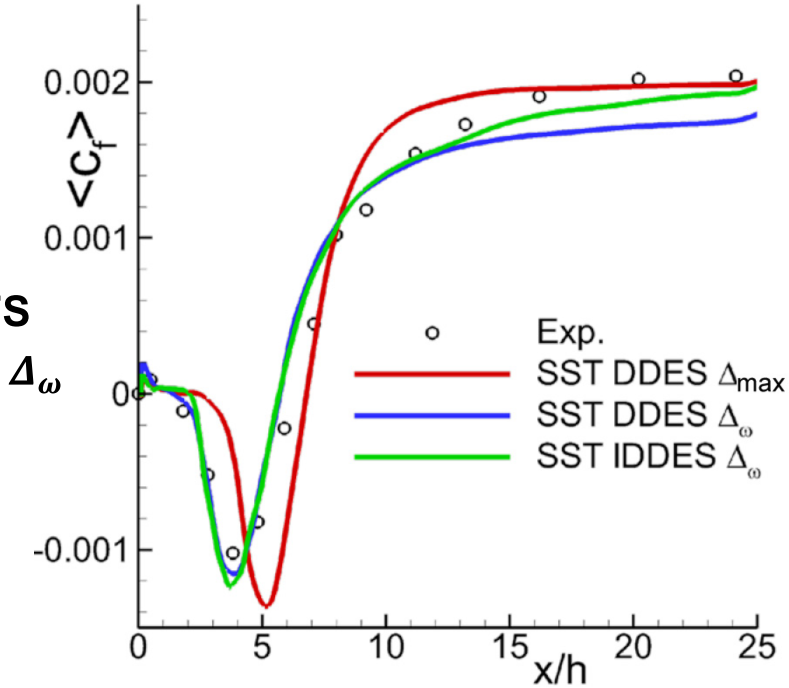
Extended approach

- **Improved Modeling** $\rightarrow$ Modified LES scale using local vorticity vector $(\vec{N})$
  - Transition from RANS to LES
    - Instead of $\Delta_{max} = \max(\Delta_x, \Delta_y, \Delta_z)$ take into account local orientation of vortices

$$\Delta_\omega = \sqrt{N_x^2 \Delta_{y,max}\Delta_{z,max} + N_y^2 \Delta_{x,max}\Delta_{z,max} + N_z^2 \Delta_{x,max}\Delta_{y,max}}$$



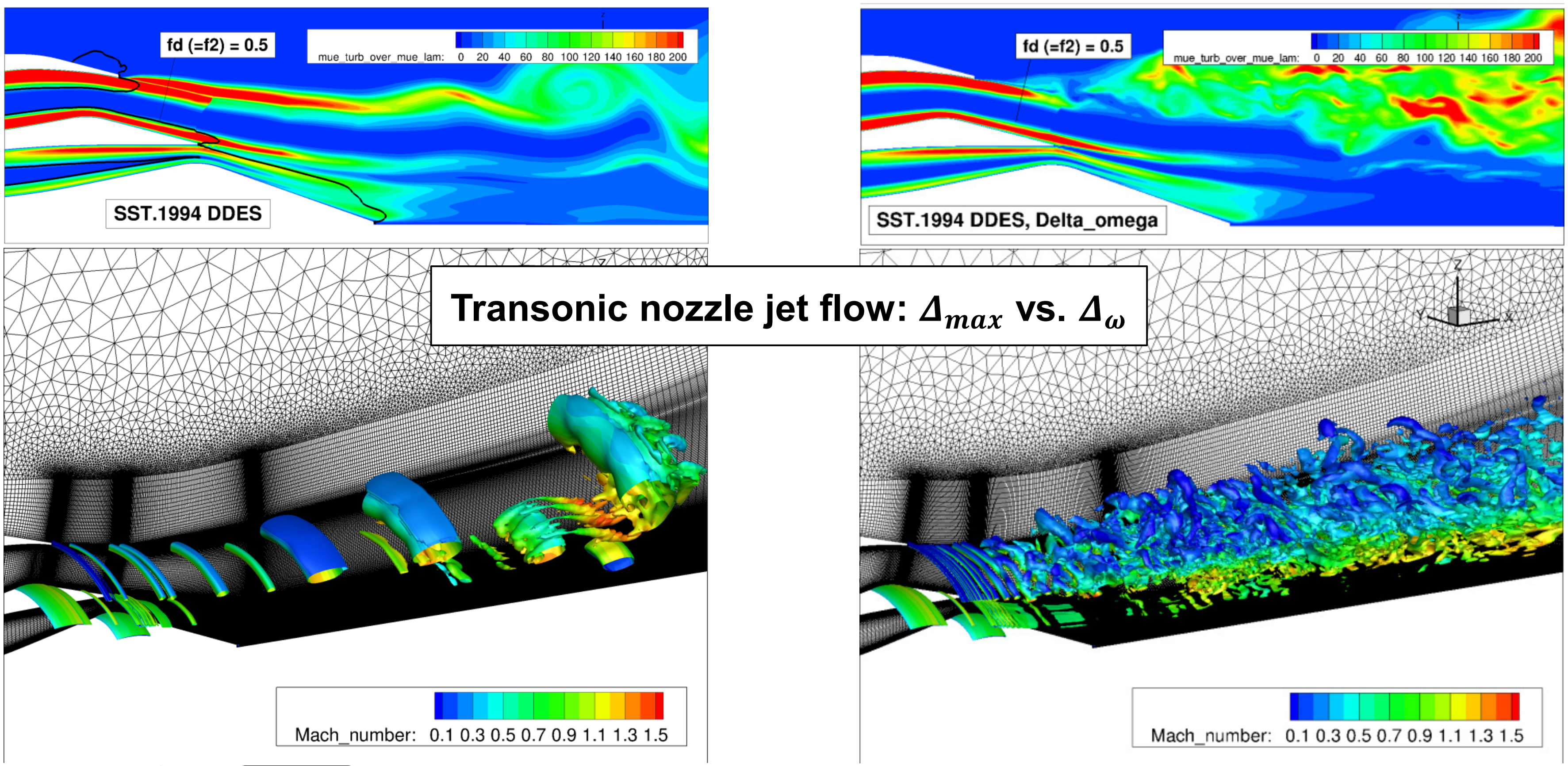
DDES of BFS with Δ_{max} vs. Δ_ω



Scale resolving simulations

Extended approach

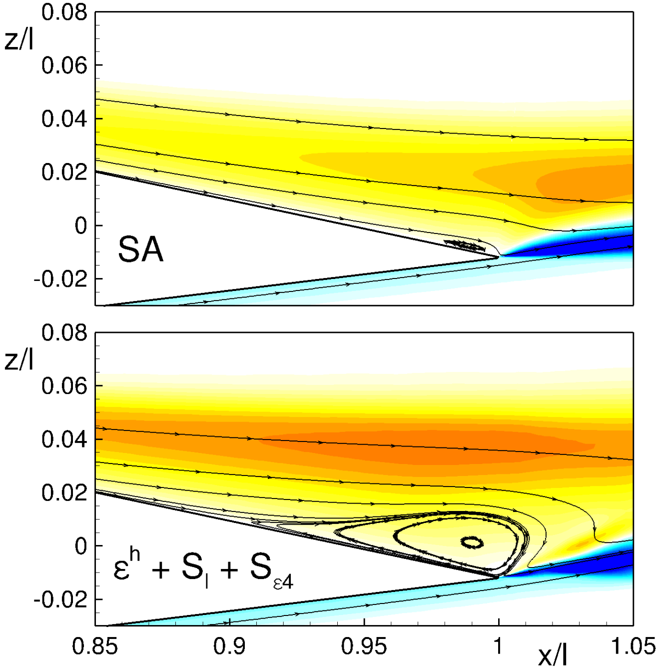
- **Improved Modeling** → Modified LES scale using local vorticity vector $(\vec{N})$



DLR C²A²S²E

Quelle: Diss. A. Probst

Scale resolving simulations



Extended approach

- Underlying RANS model
  - RANS model determines inflow boundary and location of LES region
  - DDES solution sensitivity w.r.t. RANS model
    - Low for flows with massive separation, e.g. airfoils at deep stall, step flows, …
    - Large for more practical flows, e.g. airfoil near stall, distorted intake flow, …
    - **Example:** Onera-A airfoil at maximum lift (Re = 2 Mio.)
  - DDES at flight boundaries requires more advanced RANS models, i.e. **Reynolds-stress models** (RSM)

	x_{sep}/l
Experiment	**0,83**
SA	0,96
SSG/LRR RSM	0,89
ε^h-RSM	0,88

Scale resolving simulations

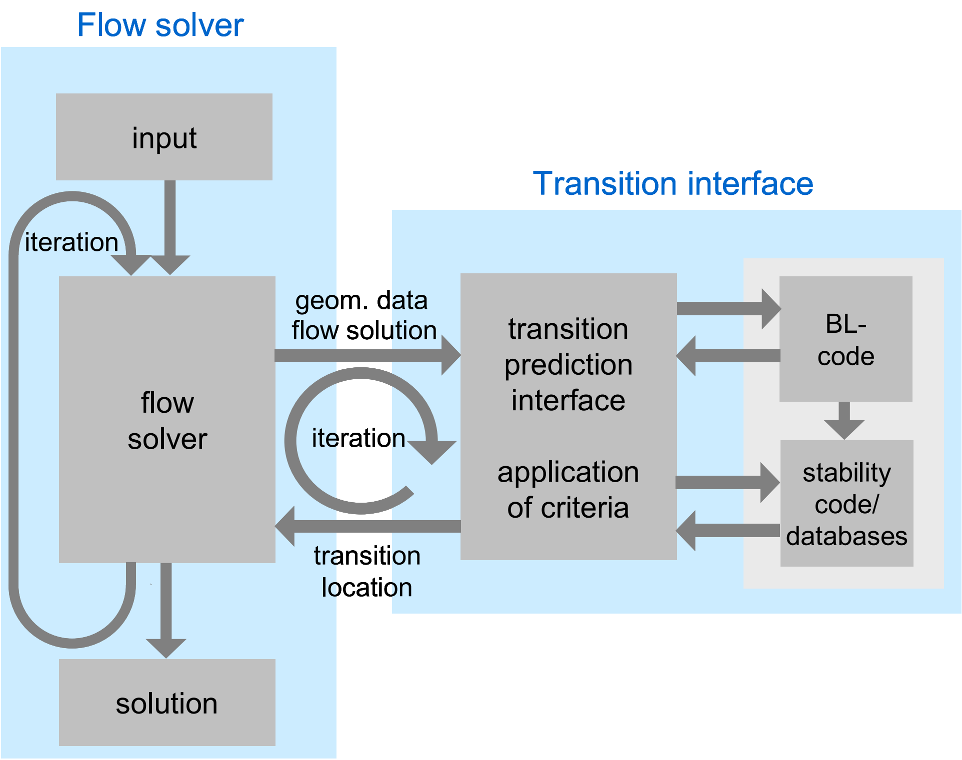
Ongoing and future developments

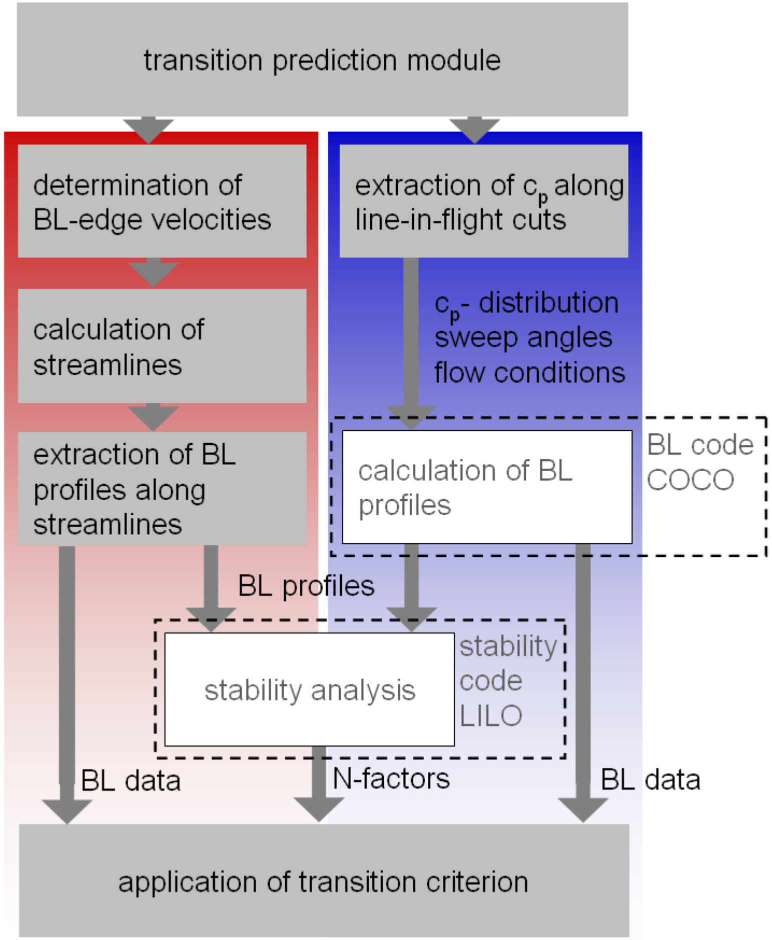
- Full integration into massively parallalized framework of TAU code for arbitrary configuration on multiple domains:
  - LD-scheme
  - Modified LES scales better supporting the physics, e.g. $\Delta_{\tilde{\omega}}$ (combination of Δ_{ω} and Δ_{max})
  - More elaborate synthetic turbulence methods, e.g. NTS's STG (synthetic turbulence generator) method
  - Synthetic turbulence methods at arbitrary actuation planes within flow field
  - ADDES
- Coupling of SSG/LRR-ω and ε^h-JHh-v2 to hybrid RANS/LES
- Combination of all above with ADDES
- Provision of SAS (Scale Adaptive Simulation) with RSM (as complementary approach)
  - SSG/LRR-ω
  - ω^h-JHh-v2

Transition Prediction and Modeling

Transition Prediction Module

- e^N method
  - Local, linear stability code
  - 2-N-factor-method: N_{TS}, N_{CF}



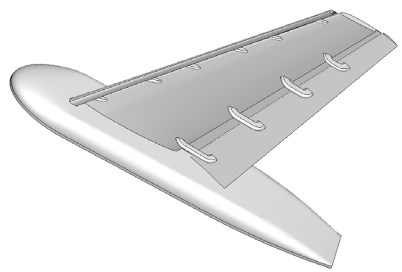


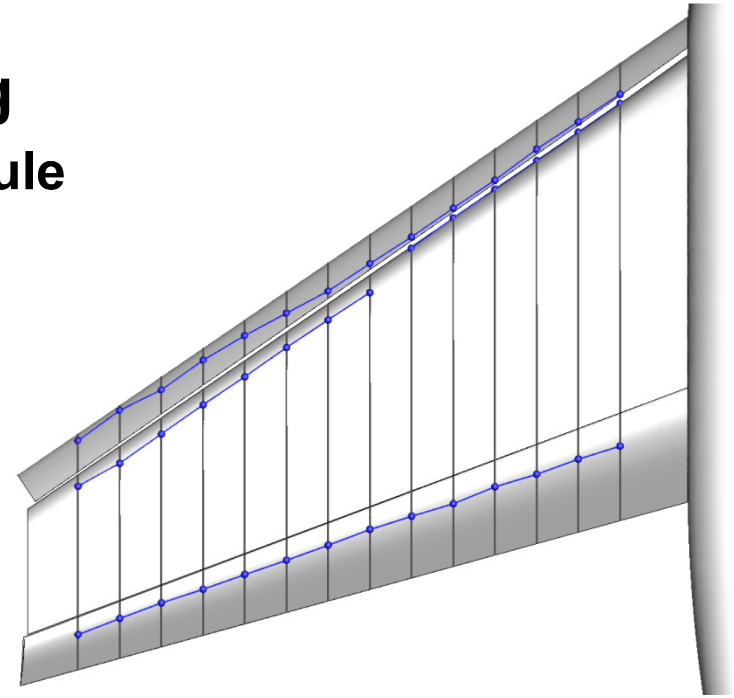
Transition Prediction and Modeling

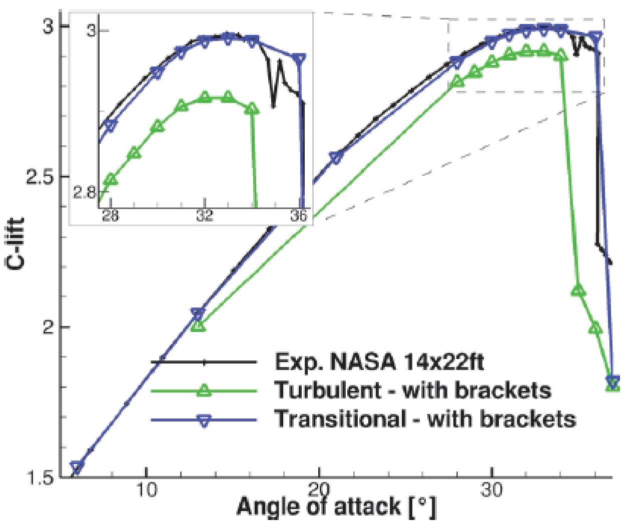
Application of Transition Prediction Module

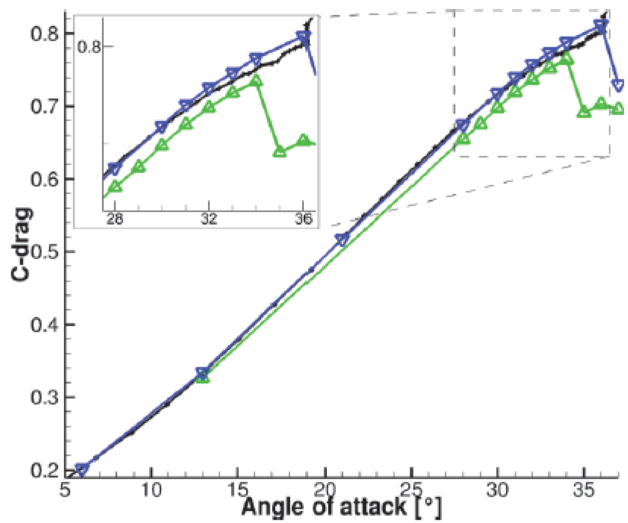
NASA trapezoidal wing, 1st HiLiPW

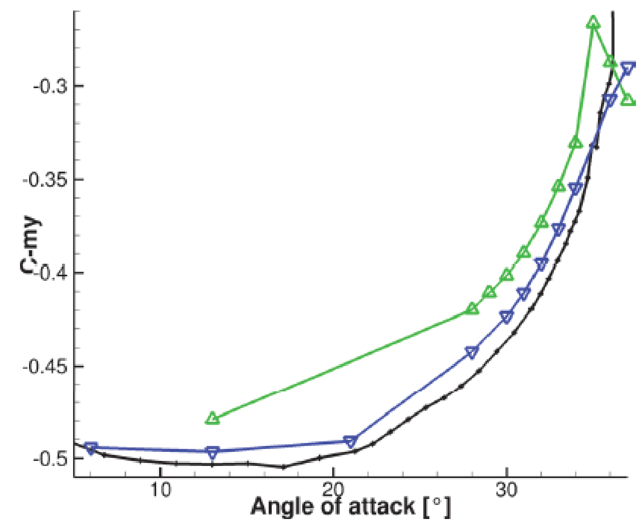
- M = 0.2, Re = 4.3×10[6], $\alpha = 6° - 36°$
- $N_{TS} = 8.5$, $N_{CF} = 8.5$











DLR

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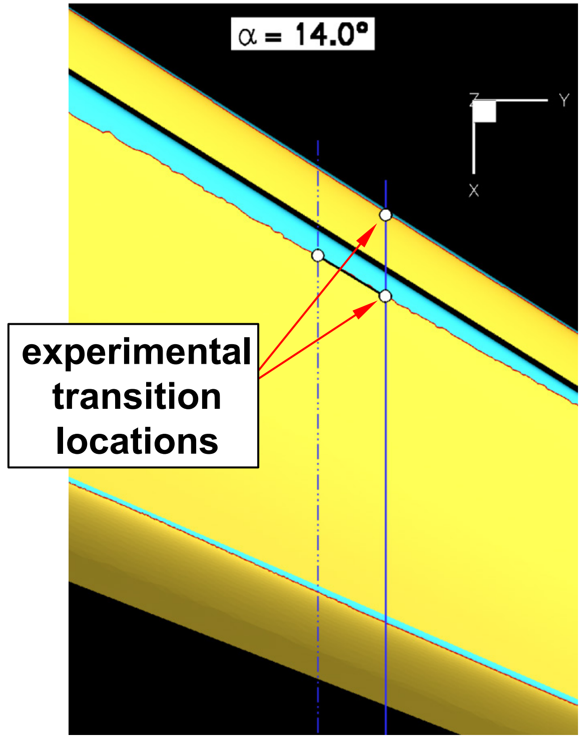
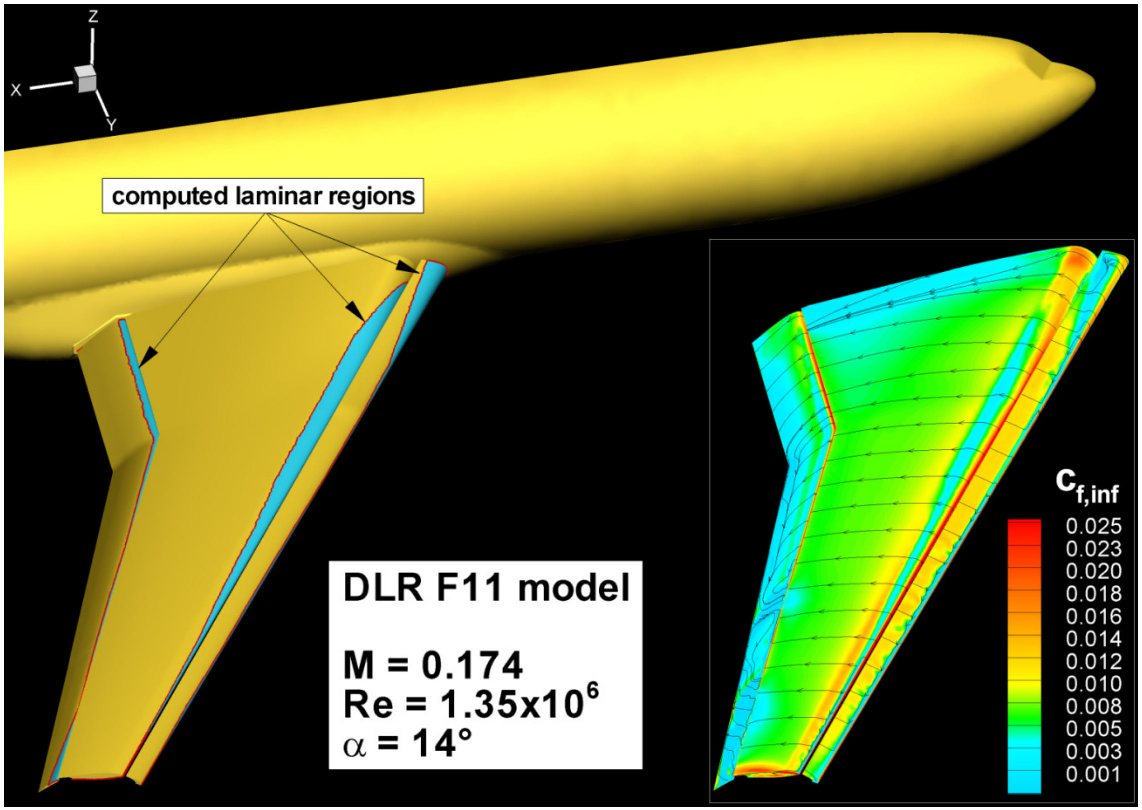
Transition Prediction and Modeling

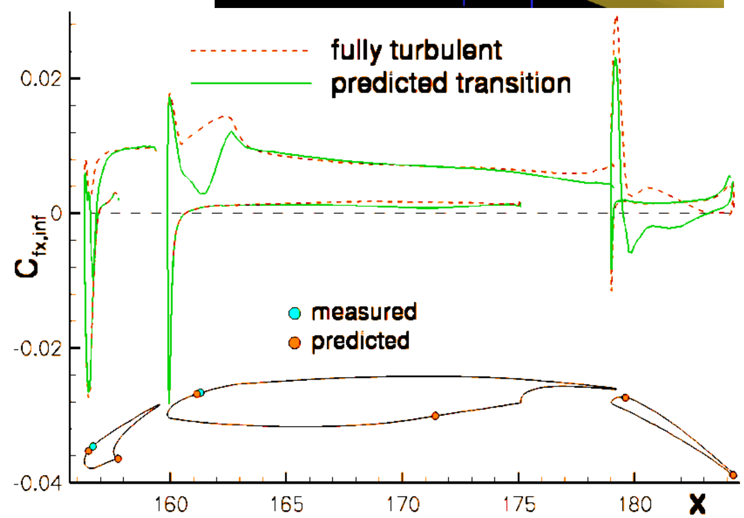
Application of Transition Prediction Module

3-element wing-body aircraft configuration

- $N_{TS} = 5$, $N_{CF} = 5$







Transition Prediction and Modeling

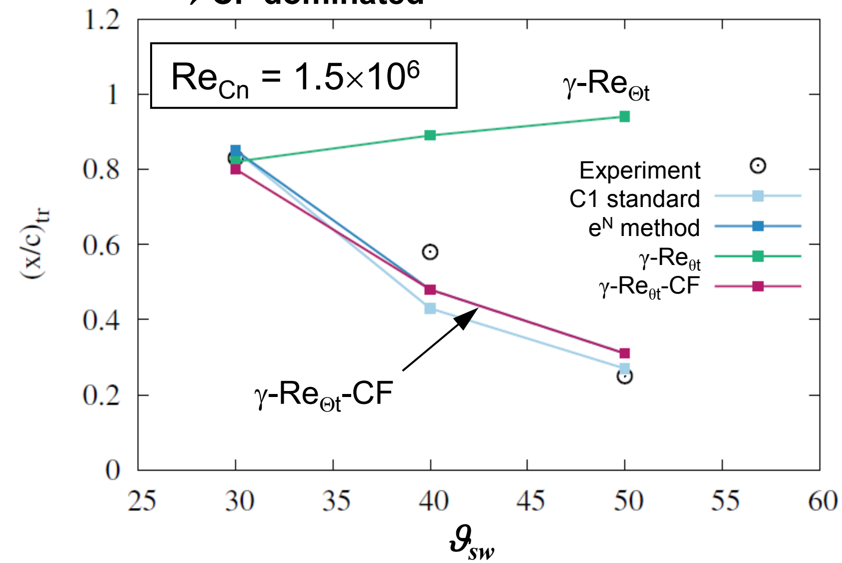
Transition Transport Modeling – γ-$Re_{\Theta t}$ model

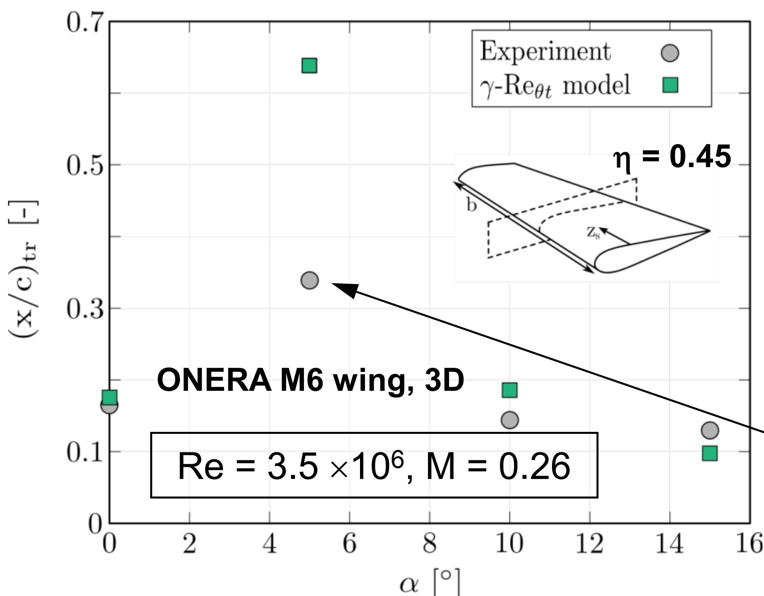
- Basic model covers TS-, bypass- and separation induced transition

Ongoing development

- Extension to CF transition → **γ-$Re_{\Theta t}$-CF model**

ONERA D, infinite swept, low M, α_n = -6°:
→ CF dominated





This transition location occurs due to cross flow transition according to linear stability theory and 2-N-factor method

Transition Prediction and Modeling

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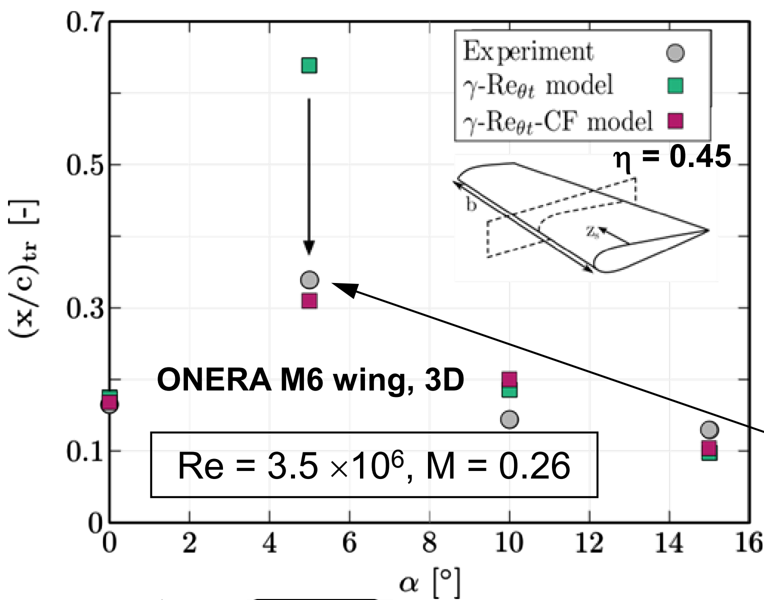

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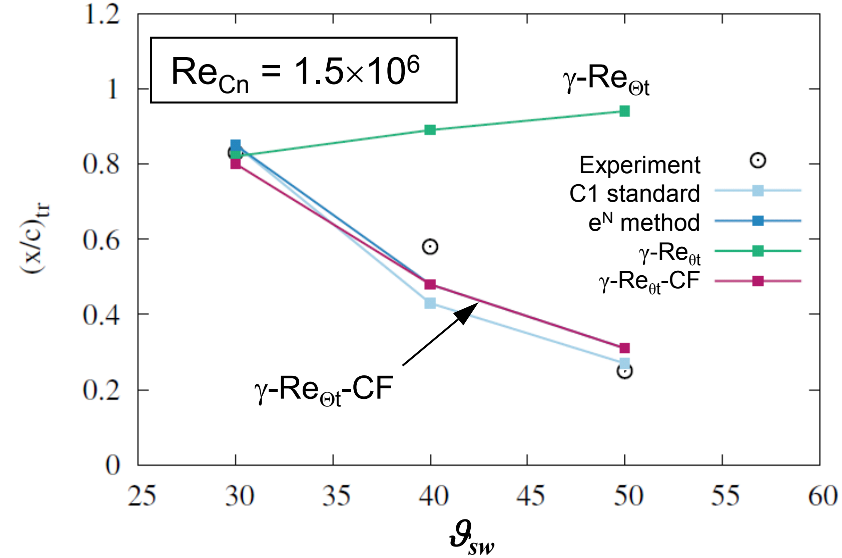


This transition location occurs due to cross flow transition according to linear stability theory and 2-N-factor method

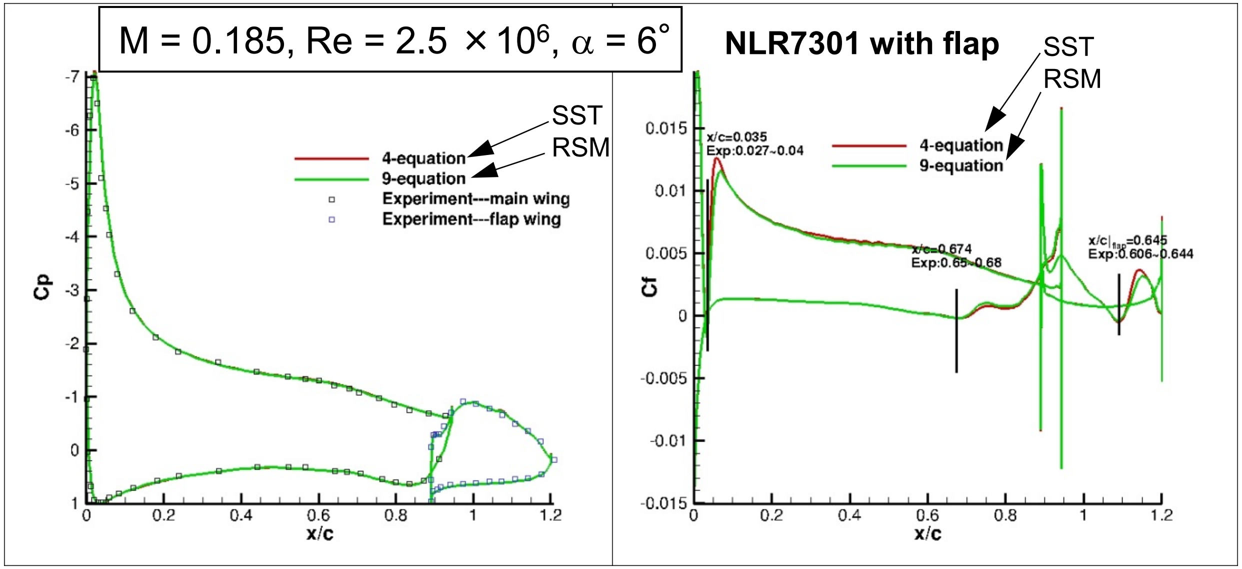
Transition Prediction and Modeling

Transition Transport Modeling – γ-$Re_{\Theta t}$ model

- **Goal:** Combination of higher modeling depth of turbulence models (physical phenomena) with transitional flows using γ-$Re_{\Theta t}$-CF model

Ongoing development

- Coupling to RSM
  - New model calibration necessary
  - First: SSG/LRR-ω



Future development

- Extensive validation using 3D configurations
- Extension to rotating systems (wind turbines, helicopters, propellers)

Conclusion

- Allover goal for CFD, accurate predictions within full flight envelope
  - Capture all major physical phenomena accurately
  - Physical modeling must be improved
- RSM are backbone for RANS computations for complete configurations
  - When influence of unsteady turbulent **fluctuations** is **insignificant**
  - Get the physical phenomena correctly
- RSM-based SRS necessary for components of aircraft or special configurations
  - When influence of *locally occuring* unsteady turbulent **fluctuations** is **significant**
  - In case of massive separation → highly unsteady, strong influence of fluctuations
  - Get the physical phenomena correctly
- Transition prediction and modeling necessary to cover the complete spectrum of phenomena turbulence models are able to capture.

Open issues/Future challenges

- Get everything into the code and have it industrialized for practical applications.
- Improve RSM from modeling point of view → bring experiments into the models